Time Delay of Radiation from Gamma-Ray Burst Sources as a Test for a Model of the Universe

Yu.S. Grishkan, V.B. Petkov *,

E.G. Vertogradova

Institute for Nuclear Research of RAS

The estimation of light velocity dispertion caused by quantum fluctuations influence on electromagnetic wave propagation in four-dimensional space-time is presented. Analytical cosmological solutions for the flat and open Universe for the case of cosmic vacuum model are obtained. The time delay of cosmic gamma-ray burst radiation is calculated. The delay is explained by propagation of dispersive electromagnetic wave in the expanding Universe. It is shown that the delay value depends on a model of the Universe. We conclude that to discern a model of the Universe measurement accuracy of parameter $\Delta t/\Delta E_{\gamma}$ should be better than 10^{-5} s/MeV.

Keywords: cosmology, gamma-ray bursts

* E-mail: petkov@neutr.novoch.ru

1 Introduction

Recently a hypothesis was suggested that global Lorentz invariance is only an approximate symmetry of nature and may be broken for elementary particles participating in various physical interactions in case of high enough energy of the particle (Amelino-Camelia et al 1998, Coleman and Glashow 1999, Stecker and Glashow 2001). As the process of this type we consider a mechanism of generation of Lorentz-noninvariant space-time metrics components caused by quantum fluctuations (Ellis et al 1998). The microscopic quantum fluctuations, which may occur on scale sizes of order the Planck length $l_{pl} \sim 10^{-33}\mathrm{cm}$, have affected fundamentally the large-scale space-time structure at the early stages of the universe creation (Hawking et al) and have caused, in particular, the universe birth from vacuum and the stage of quantum inflation (Vertogradova and Grishkan 2000). But now the same fluctuations also exists and may have an influence on the rays of light propagating through the space-time. Indeed as it is shown by Ellis et al (1998, 2000a) the fluctuations, constituting the so-called space-time foam, transform macroscopic properties of space-time metrics and generate non-diagonal components of the metrics $g_{0\alpha}$, so that

$$g_{00} = -1, \quad g_{\alpha\beta} = \delta_{\alpha\beta}, \quad g_{0\alpha} = \frac{u_\alpha}{c}$$

Here Greek letters have values $\alpha, \beta = 1, 2, 3$, c is the velocity of light constant. As a result, the whole space-time is rotated at a velocity proportional to $u_\alpha/c \ll 1$. A vector of rotation velocity u_α breaks global Lorentz invariance (Coleman and Glashow 1999) and thus transforms dispersion properties of light waves propagating through the space-time

$$c(E) = c\left(1 - \frac{u}{c}\right) \tag{1}$$

where $E = \hbar\omega$ is the photon energy of frequency ω, u is the absolute value of the vector u_α. The quantum-gravity theory, particularly the space-time foam theory (Ellis et al 2000a), predicts the ratio of velocities appearing in (1) is proportional to the ratio of the photon energy E to effective quantum-gravity energy scale M_{QG}

$$\frac{u}{c} \sim \frac{E}{M_{QG}} \tag{2}$$

Consequently the delay in the arrival times of photons of different energies and hence velocities propogating in the space-time foam from distant source of radiation is estimated as

$$\Delta t = \frac{\Delta L(\Delta u)}{c} \sim \frac{L}{c}\frac{\Delta u}{c} \sim \frac{L}{c}\frac{\Delta E_\gamma}{M_{QG}} \tag{3}$$

where L is a source distance, ΔE_γ is the difference of energies of detected photons.

As the radiation from distant sources propagates through the space-time foam there must be the delay in the arrival times of photons depending on the photon energy. If we succeed in measuring this delay we will be able to test quantum-gravity ideas. Moreover it is the constant M_{QG} that characterize the energy scale of the effects of quantum gravity. Therefore it will be possible to estimate the quantum-gravity energy scale M_{QG} in the following way

$$M_{QG} = \frac{L}{c}\frac{\Delta E_\gamma}{\Delta t} \tag{4}$$

It is worth noting that the ratio E/M_{QG} is negligible. The time delay effect may be observable only for cosmological distances. It is also clear that the higher the energy of radiation the better. Therefore γ – ray bursts sources of extragalactic origin are considered as high-energy radiation sources of interest. The time delay in the arrival times of photons of different energies from γ – ray burst sources was studied by Ellis et al (2000b) based on BATSE and OSSE observations (Paciesas et al 1999, OSSE Collaboration 1999). The

calculation of the source distance in formulas (3), (4) may be realized for certain model of the universe. In this way theoretical calculation of the time delay is universe-model dependent. The approach described above implies that the photons of different energies are radiated by the source of γ – ray burst at the same time and the photons time delay is the effect of quantum gravity and is not caused by processes inside the source of radiation.

2 Time delay-redshift diagram – theoretical calculation

We obtain here the time delay value of radiation in the expanding universe in terms of the cosmic vacuum model (Chernin 2001). The exact first integral of Einstein's equation for this model is

$$\frac{1}{2}\,\dot{a}^2 = \frac{1}{2}\,A_V^{-2}a^2 + (A_D + A_B)\,a^{-1} + \frac{1}{2}\,A_R^2 a^{-2} - \frac{1}{2}\,k \tag{5}$$

where $a(t)$ is the scale factor of the universe, $k = 0, \pm 1$ is the space curvature sign (it corresponds to flat, closed and open universe). The derivative in equation (5) means $\dot{a} = da/d(ct)$, where t is physical time. The values of the Friedmann's integrals are obtained experimentally: $A_V \sim a_0 \sim 10^{28}$ cm is the cosmic vacuum constant, $A_D \sim 10^{-1}A_V$ is the dark matter constant, $A_B \sim 10^{-2}A_V$ is the constant of baryon's subsystem, $A_R \sim 10^{-2}A_V$ is the constant of radiation of all types, a_0 is the current value of the scale factor of the universe (which is calculated for flat model of Friedmann type $a_0 \simeq t_0\,c$) and the current age of the universe is $t_0 \sim 2.8 \times 10^{17}\mathrm{s} \sim 10\,\mathrm{Gyr}$. The model of Friedmann type means here matter-dominated epoch of the universe evolution.

Within the framework of model under discussion the value of the space curvature sign

k is usually ignored because the sign have not significant influence on the fate of the cosmic expansion and hence on the dynamics of observable cosmological objects. We will show however that the influence is very important for the precise effect of time delay. Therefore the k value will not be neglected below. We consider here the values $k = 0$ (flat model of cosmic vacuum) and $k = -1$ (open model of cosmic vacuum). As regards the closed model $k = 1$, theoretical interpretation of time delay effect for this model is difficult for many reasons.

We consider baryon-vacuum epoch of the universe evolution. The scale factor during the epoch of interest is $a \gg A_R^2/A_D$ ($z \ll 1000$), so the constant of radiation A_R in equation (5) is appropriate to be neglected. Therefore we can find the time t for given value of the scale factor a in the form

$$\frac{t - t_0}{t_0} = \int_{a_0}^{a} \frac{d(a/a_0)}{\left[(a/a_0)^2 + (a_1/a_0)\,(a/a_0)^{-1} - k\right]^{1/2}} \tag{6}$$

where $a_1 = 2\,(A_D + A_B)$. Besides the analytical solution in terms of primitive functions is obtained for $k = 0$

$$\frac{t - t_0}{t_0} = \frac{2}{3} \ln \left\{ \frac{(a/a_0)^{3/2} + \left[(a/a_0)^3 + (a_1/a_0)\right]^{1/2}}{1 + [1 + (a_1/a_0)]^{1/2}} \right\} \tag{7}$$

The scale factor dependence in (6), (7) can be parametrized by the redshift z according to standard formula $a/a_0 = 1/(1+z)$. As a result the integral in equation (6), for example, takes the form

$$\frac{t - t_0}{t_0} = -\int_{1}^{z+1} \frac{d\xi}{\xi\,[1 - k\xi^2 + (a_1/a_0)\,\xi^3]^{1/2}} \tag{8}$$

Taking into account expressions (1)–(3) and (8) we obtain the time delay of radiation from distant source Δt in the form

$$\frac{\Delta t}{t_0} = \int_{1}^{z+1} \frac{\Delta u}{c} \frac{d\xi}{\xi\,[1 - k\xi^2 + (a_1/a_0)\,\xi^3]^{1/2}}$$

or

$$\frac{\Delta t}{t_0} = \frac{\Delta E_\gamma}{M_{QG}}\, \Phi(z,k) \tag{9}$$

$$\text{where} \quad \Phi(z,k) = \int_1^{z+1} \frac{d\xi}{\left[1 - k\xi^2 + (a_1/a_0)\,\xi^3\right]^{1/2}}$$

Here we have taken into consideration the fact that the photon energy varies during the process of the Universe evolution depending on the redshift as $E = E_\gamma(1+z)$.

Up to a constant the asymptotic form of time delay formula (9) for high-redshift objects $z \to \infty$ is in agreement with appropriate expression obtained by Ellis et al (2000b).

$$\frac{\Delta t}{t_0} = \frac{\Delta E_\gamma}{M_{QG}}\, z, \quad z \ll 0.7 \quad (z \to 0) \tag{10}$$

$$\frac{\Delta t}{t_0} = \frac{\Delta E_\gamma}{M_{QG}} \left(\frac{a_0}{a_1}\right)^{1/2} 2\,\tilde{z}, \quad z \gg 0.7 \quad (z \to \infty) \tag{11}$$

where $\tilde{z} = 1 - (1+z)^{-1/2}$ and $a_0/a_1 \sim 5$. The formula (10) corresponds to the universe expansion according to the law of Hubble and formula (11) – to the universe expansion of flat Friedmann type.

We'd like to note that the model of cosmic vacuum gives the expression (11) for the time delay only at the limit of high redshift $z \to \infty$. Because of this the time delay-redshift dependence is different for the cosmic vacuum model and for the flat Friedmann model discussed by Ellis et al (2000b). This fact is quite important for experimental data analysis.

3 The time delay experimental data and the possibility of determination of the fate of the cosmic expansion

The Picture 1 illustrates theoretical dependences of parameter $\Delta t/\Delta E_\gamma$ as a function of redshift z. The dependences were computed from formula (9) for different cosmological models: Curve 1 corresponds to the flat model of Friedmann type, Curve 2 corresponds to the flat model of cosmic vacuum and Curve 3 corresponds to the open model of cosmic vacuum. The effective quantum-gravity energy scale is set to be equal to the Planck energy scale 10^{19} GeV. From this Picture it is possible to determine the fate of the cosmic expansion when the measurement accuracy of parameter $\Delta t/\Delta E_\gamma$ is better than 10^{-5} s/MeV.

Thus for the cosmological model selection (or for estimation of the quantum-gravity energy scale) measurements of γ – ray bursts redshifts and the comparative time delay of photons of different energies are required. The paper of Ellis et al. (2000b) contains experimental data from BATSE catalog (Paciesas et al. 1999) and OSSE data (OSSE Collaboration 1999) for five γ – ray bursts whose redshifts are known: 1) GRB970508, $z = 0.835$, 2) GRB971214, $z = 3.14$, 3) GRB980329, $z = 5.0$ 4) GRB980703, $z = 0.966$, 5) GRB990123, $z = 1.60$. The energy ranges of photons from this γ – ray burst sources observed by BATSE are: Channel 1 between 20 and 50 keV and Channel 3 between 100 and 300 keV. The difference of arrival times for Channel 1 and Channel 3 photons is of our interest. Moreover two γ – ray bursts – GRB980329 and GRB990123 – were also detected by OSSE detector (OSSE Collaboration 1999) in a single channel with

energy range $1-5$ MeV. The experimental time delay in this case is the difference of arrival times of photons for OSSE data and Channel 3 of BATSE. Both BATSE and OSSE experimental values of parameter $\Delta t/\Delta E_\gamma$ as a function of redshift z obtained according to the paper of Ellis et al. (2000b) are given at the Picture 2. We compare Picture 1 with Picture 2 and conclude that at present moment measurement accuracy does not allow to determine the fate of the universe expantion.

4 Conclusions and prospects

We believe that analysis of more statistically significant number of γ – ray bursts in the future with measured redshifts and delays in the arrival times of photons of different energies will allow us to realize theory-experiment comparison more effectively. When this reliable data appear it will be possiable to test quantum-gravity effects, select cosmological models of different topology of embedded three-dimensional space ($k = 0, -1, 1$) and obtain more precise values of the approximatly known Friedmann's integrals, particularly the integral A_V. For the time being we can only use the available experimental data (Ellis et al. 2000b) and estimate the quantum-gravity energy scale as

$$M_{QG} \gtrsim 10^{15}\ \mathrm{GeV}$$

In the case of $M_{QG} \sim M_{pl} \sim 10^{19}$ GeV we conclude that for the investigation of effects of delays in the arrival times of photons from cosmological γ – ray burst sources measurement accuracy of ratio $\Delta t/\Delta E_\gamma$ should be better than $\sim 10^{-5}$ s/MeV.

The research was supported by grant RFBR 00-02-16095.

References

Amelino-Camelia G., Ellis J., Mavromatos N.E., Nanopoulos D.V., Sarkar S.) // Nature, 1998, v. 393, p. 763.

Chernin A.D. // Uspehi phis. nauk, 2001, v. 171, N11, p. 1153.

Coleman S., Glashow S.L. // Phys. Rev. D, 1999, v. 59, p. 116008.

Ellis J., Kant P., Mavromatos N.E., Nanopoulos D.V., Winstanley E. // Mod. Phys. Lett., 1998, v. A13, p. 303.

a Ellis J., Mavromatos N.E., Nanopoulos D.V. // CERN-2000-136; preprint gr-qc/0005100.

b Ellis J., Farakos K., Mavromatos N.E., Mitsou V.A., Nanopoulos D.V. // Astrophys. J., 2000, v. 535, p. 139.

Hawking S., Page D.N., Pope C.N. // Nucl. Phys. B, 1980, v. 170 [FSH], p. 283.

OSSE Collaboration // Gamma Ray bursts time profiles, 1999; http://www.astro.nwu.edu/astro/OSSE/bursts/.

Paciesas W.S. et al // Astrophys. J. Suppl. Ser., 1999, v. 122, p. 465.

Stecker F.W. and Glashow S.L. // Astropart. Phys., 2001, v. 16, p. 97.

Vertogradova E.G., Grishkan Yu.S. // Astronomy Reports, 2000, v. 77, N3, p. 1.

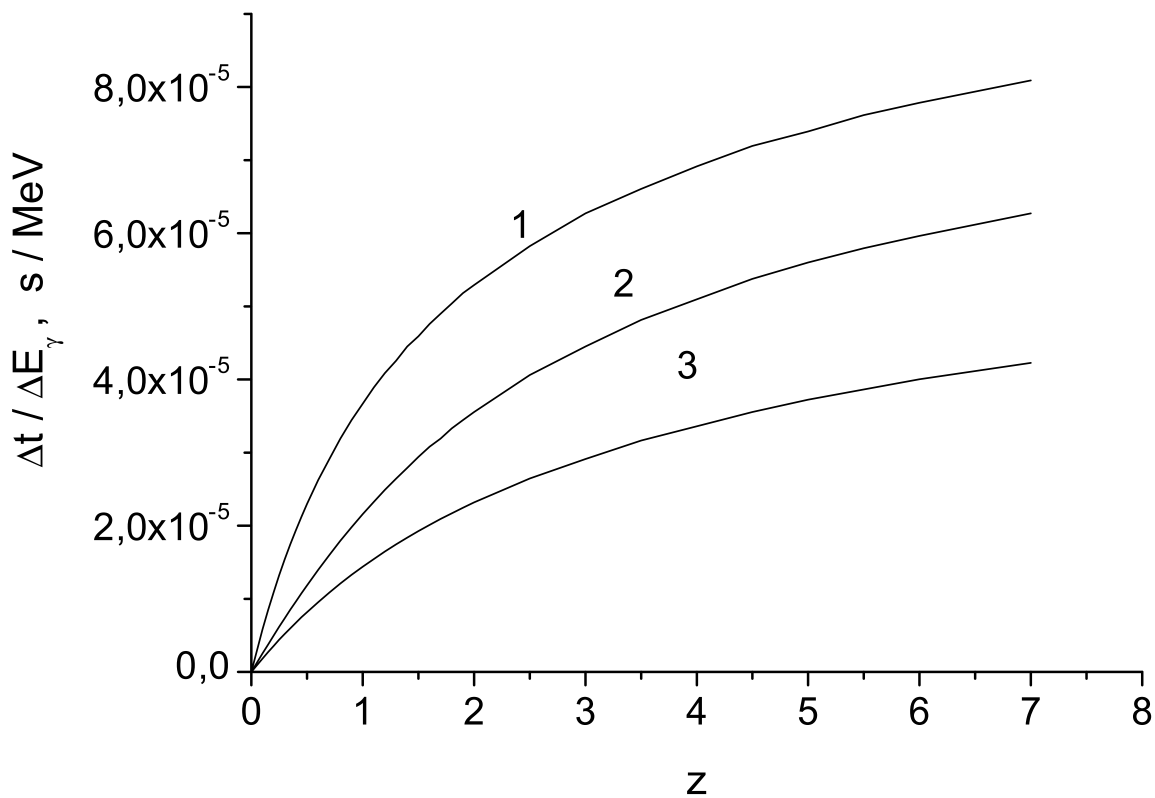

Figure 1: Theoretical Results. Line 1 corresponds to the solution of Flat Friedmann type, Line 2 - to the Flat Model of Cosmic Vacuum and Line 3 - to the Open Model of Cosmic Vacuum

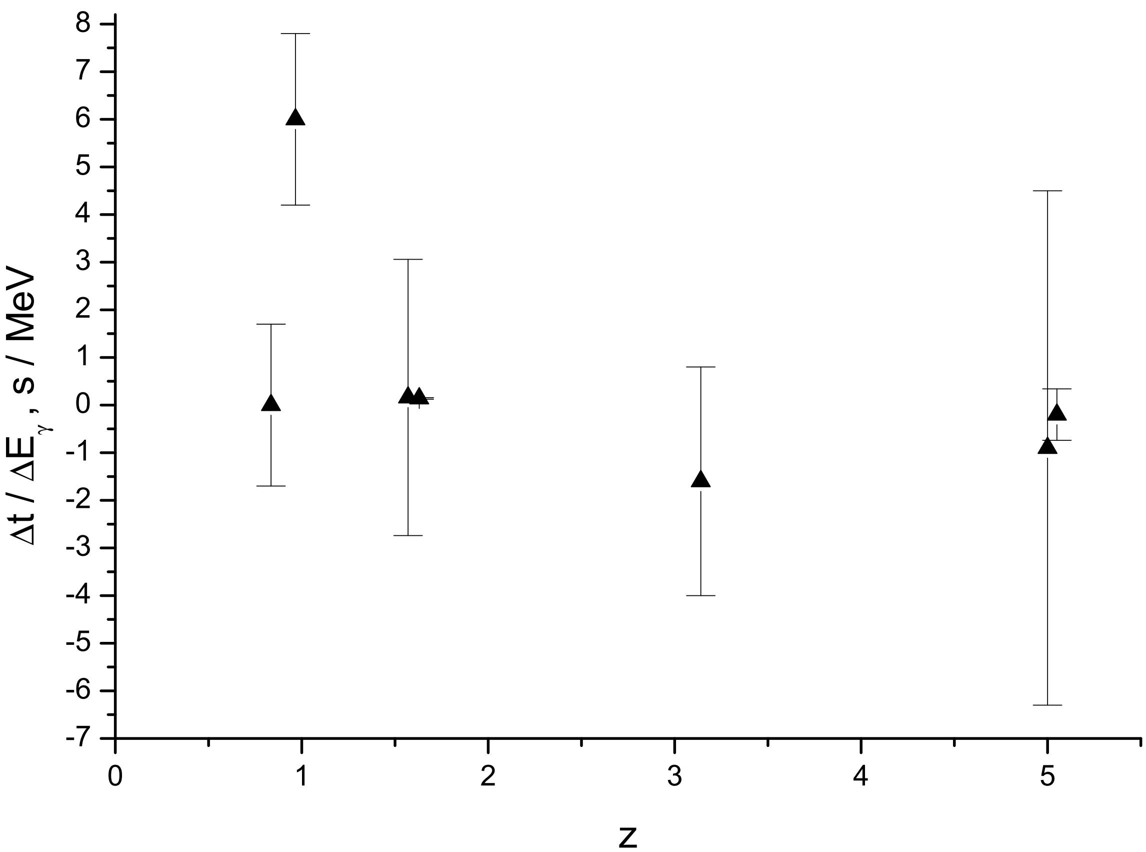

Figure 2: Results of Fits to the Gamma-Ray Burst Data from BATSE and OSSE